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# The Accreting White Dwarf in SS Cygni Revealed[1]

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## ABSTRACT

We have carried out a combined Hubble Space Telescope (HST/GHRS) and Far Ultraviolet Spectroscopic Explorer (*FUSE*) analysis of the prototype dwarf nova SS Cygni during quiescence. The *FUSE* and HST spectra were obtained at comparable times after outburst and have matching flux levels where the two spectra overlap. In our synthetic spectral analysis, we have used SS Cygni's accurate HST FGS parallax giving $d = 166$ pc, a newly determined mass for the accreting white dwarf (Bitner et al. 2007) of $M_{wd} = 0.81 M_{\odot}$ (lower than the previous, widely used $1.2 M_{\odot}$) and the reddening ($E_{B-V}$) values 0.04 (Verbunt 1987; La Dous 1991) & 0.07 (Bruch & Engel 1994) derived from the 2175 Å

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absorption feature in the IUE LWP spectra. From the best-fit model solutions to the combined HST + *FUSE* spectral energy distribution, we find that the white dwarf is reaching a temperature $T_{eff} \approx 45 - 55,000$ K in quiescence, assuming $\log(g) = 8.3$ with a solar composition accreted atmosphere. The exact temperature of the WD depends on the reddening assumed and on the inclusion of a quiescent low mass accretion rate accretion disk. Accretion disk models alone fit badly in the *FUSE* range while, and if we take the distance to be a free parameter, the only accretion disk model which fits well is for a discordant distance of at least several hundred pc and an accretion rate ($\sim 10^{-8} M_{\odot}$/yr) which is unacceptably high for a dwarf nova in quiescence. We discuss the implications of the white dwarf's temperature on the time-averaged accretion rate and long term compressional heating models.

*Subject headings:* accretion, accretion disks - novae, cataclysmic variables - white dwarfs

## 1. Introduction

SS Cygni is a prototype dwarf nova, a subclass of the cataclysmic variable group of binary stars. Cataclysmic variables contain a white dwarf and a larger radius, less massive, donor star. The donor star fills its Roche lobe and its matter has gradually been cannibalized by the white dwarf. In dwarf novae the matter feeds into a disk around the white dwarf and continues to build up the disk mass until the disk reaches a critical temperature at which time the mass collapses onto the white dwarf and releases gravitational potential energy as radiation. This results in a roughly periodic increase in brightness of the system.

SS Cyg is one of the best-studied dwarf novae. It has an orbital period of 6.6 hr (well above the period gap) and a $\sim 50$ day recurrence time between dwarf nova outbursts (Cannizzo & Mattei 1992; Cannizzo 1993). These factors and its well-studied history have made it a key target of our ongoing studies to understand how disk accretion affects the white dwarf. Observations must be taken when the system is in quiescence because in such a state, the disk is least luminous which offers a favorable opportunity to detect the radiation of the white dwarf photosphere. However, the source of far ultraviolet light during the quiescence of dwarf novae remains controversial. This is especially true in dwarf novae with orbital periods above the CV period gap, which tend to have higher mass transfer rates, larger accretion disks and more massive secondary stars. Therefore, during quiescence it is possible that some portions of the remaining disk may still be optically thick and dominate the far ultraviolet (FUV) flux of the system.

The inclination of its orbit is $\sim 51^\circ$ (Bitner et al. 2007) while its white dwarf mass has been reported to be $1.2M_\odot$ (Shafter 1983) and secondary mass $0.7M_\odot$. The system has an accurate parallax measured with the Hubble Space Telescope fine guidance sensor (Harrison et al. 2000) yielding a parallax distance of $166^{+14}_{-12}$ pc. Holm & Polidan (1988) first noted the possible detection of the underlying accreting white dwarf from the occasional appearence of Ly$\alpha$ absorption in some IUE spectra obtained during quiescence. However, despite a number of attempts to measure the white dwarf's temperature and quantify its contribution to the FUV flux, the uncertain contribution of the accretion disk and other possible unidentified source(s) of FUV emission, the "second component", rendered any such measurements suspect (Holm 1988; Lesniak & Sion 2003; Long et al. 2005).

Recently however, we retrieved archival *FUSE* and HST spectra, both obtained during different quiescent intervals of SS Cygni but with closely matching flux levels in the wavelength range where HST/GHRS and *FUSE* overlap ($\sim 1150 - 1190$ Å ). Also a new mass determination for the white dwarf has now been derived by Bitner et al. (2007): $0.81M_\odot \pm 0.18$, significantly lower than the earlier value of $1.2M_\odot$. Using this lower mass and the parallax distance of 166 pc, we have reexamined the nature of the hot component with synthetic spectral models of high gravity photospheres and optically thick accretion disks. This assessment is presented below.

In the next section we give details of the archival spectra, in section 3 we present our spectal modeling tools and method, results are presented in section 4 and discussed in the concluding section.

## 2. Archival Observations

The archival HST GHRS spectrum was taken on JD 2450352 (1996 September 26), in mid-quiescence, 17 days after SS Cygni reached quiescence and 21 days after the previous outburst. The HST spectrum is a combination of two individual spectral segments Z3DV0204T (1150 Å- 1435 Å) and Z3DV0205T (1377 Å- 1663 Å) taken in ACCUM mode with the GHRS spectrograph with the G140L grating and LSA aperture (of size 1.74"). The two spectral segments, one at each grating setting, had an exposure time of 2176s each, and there was a 32.25 second time gap in an otherwise nominal exposure. The GHRS observations were calibrated using the standard pipeline CALHRS, and were retrieved as VO-Tables using VOSpec.

The archival *FUSE* spectrum was taken on JD 2452156.5 (2001 September 4), 18 days after the previous outburst, and 13 days after the system first entered quiescence. The

*FUSE* spectrum (P2420101), was a combined spectrum of 8 separate exposures taken through the 30"x30" LWRS Large Square Aperture in TIME Tag mode. The total good exposure time was $\sim$ 18ks, varying slightly for each spectral channel. The observations were carried out mostly during NIGHT time. The *FUSE* observations were processed with CalFUSE version v3.2.3 (Dixon et al. 2007). We follow the same procedure we used previously for the postprocessing (co-addition, alignment and weight of the spectral channels) of the *FUSE* data (see e.g. Godon et al. (2006)).

The combined *FUSE* + GHRS spectrum of SS Cyg is presented in Fig.1 (see section 4 for the model fit). The spectrum is characterized by strong emission lines originating in an optically thin region in the disk or above it, as inferred from their rotational broadening (see Long et al. (2005) for a rigourous analysis of these lines in the GHRS spectra). In the very short wavelengths of *FUSE* the broad emission lines from N IV, S VI and H I (Ly$\delta$ and higher) merge together and produced an apparent rise of flux ($<$ 950 Å), which we do not attempt to model. In the fitting (section 4) we mask all the emission lines and these appear in blue in Fig.1. It is likely that around 1060-1080 Å and 1110-1120 Å some additional emission is present.

## 3. Synthetic Spectral Modeling

We adopted model accretion disks from the optically thick disk model grid of Wade & Hubeny (1998). In these accretion disk models, the innermost disk radius, $R_{in}$, is fixed at a fractional white dwarf radius of $x = R_{in}/R_{wd} = 1.05$. The outermost disk radius, $R_{out}$, was chosen so that $T_{eff}(R_{out})$ is near 10,000 K since disk annuli beyond this point, which are cooler zones with larger radii, would provide only a very small contribution to the mid and far UV disk flux, particularly the FUV bandpass ($\sim 900 - 1700$ Å). The mass transfer rate is assumed to be the same for all radii.

Theoretical, high gravity, photospheric spectra were computed by first using the code TLUSTY (Hubeny 1988) to calculate the atmospheric structure and SYNSPEC (Hubeny & Lanz 1995) to construct synthetic spectra. We compiled a library of photospheric spectra covering the temperature range from 15,000 K to 70,000 K in increments of 1000 K, and a surface gravity range, $\log(g) = 7.0 - 9.0$, in increments of 0.2 in $\log(g)$.

The reddening of the system was taken from estimates listed in the literature, determined from the strength of the 2200 Å interstellar absorption feature. Verbunt (1987) and La Dous (1991) both give E(B-V)=0.04 while the more recent work of Bruch & Engel (1994) gives E(B-V)=0.07. Both values are much smaller than the galactic reddening in the direction

of SS Cyg which is pretty large ($\sim$ 0.5) in agreement with the fact that SS Cyg is rather nearby with a distance of *only* 166 pc. The combined spectrum was de-reddened with the IUERDAF IDL routine UNRED assuming both E(B-V)=0.04 and E(B-V)=0.07.

After masking emission lines in the spectra, we determined separately for each spectrum, the best-fitting white dwarf-only models and the best-fitting disk-only models using a $\chi^2$ minimization routine. A $\chi^2$ value and a scale factor were computed for each model fit. The scale factor, $S$, normalized to a kiloparsec and solar radius, can be related to the white dwarf radius R through:

$$F_{\lambda(obs)} = SH_{\lambda(model)}, \qquad where \quad S = 4\pi R^2 d^{-2},$$

and $d$ is the distance to the source. For the white dwarf radii, we use the mass-radius relation from the evolutionary model grid of Wood (1995) for C-O cores. We combined white dwarf models and accretion disk models using a $\chi^2$ minimization routine called DISKFIT. Using this method the best-fitting composite white dwarf plus disk model is determined based upon the minimum $\chi^2$ value achieved, visual inspection of the model, consistence with the continuum slope and Ly$\alpha$ region, and consistence of the scale factor-derived distance with the adopted trigonometric parallax distance.

## 4. Synthetic Spectral Fitting Results

We used an accretion disk model, a white dwarf photosphere, and a combination of both in our analysis. The disk models used were optically thick, steady state accretion models with solar abundances. They are considered a reasonable first approximation to the spectral shape of the disk in quiescence. In the disk models, we first adopted an inclination of 41° and 60° directly from the grid of models of Wade & Hubeny (1998). Only after a satisfactory best fit was obtained with the correct (parallax) distance, did we then generate disk models (using TLUSTY, SYNSPEC and DISKSYN) with an inclination of 50°, closer to its derived value of $51° \pm 5$ (Bitner et al. 2007). The photosphere models were generated using TLUSTY and SYNSPEC. In the following we used the parallax distance of 166 pc, and the mass of $0.8 M_{\odot}$ ($\log(g) = 8.3$) (Bitner et al. 2007). We assumed reddening values of E(B-V) = 0.04 and 0.07. A summary of the model fits is given in Table 1.

We started our fitting with single accretion disk models alone assuming both E(B-V)=0.04 & 0.07. We ran disk model fits and found that the best fit (lowest $\chi^2$) had a mass accretion rate far too large for quiescence and a distance much larger than 166 pc.

Next, we tried single white dwarf atmosphere models, first dereddening assuming E(B-V)=0.04. Since almost all the lines are in emission (possibly from an optically thin region

in the disk and/or corona), it makes it difficult to assess the rotational velocity broadening and chemical abundances based on the absorption lines. Nevertheless, for all WD models we assumed solar abundances and a canonical projected rotational velocity of 200 km/s, and checked that the value of the $\chi^2$ did not depend on $V_{rot} \sin i$ as long as it was a few hundred km/s. The best fit least $\chi^2$ WD model has a temperature $T_{eff} = 40,000$ K and $\chi^2 = 1.637$, but with a distance of only 138 pc. A model with $T_{eff} = 47,000$ K gave the right distance with a slightly larger $\chi^2$, namely 1.990. Next we ran single WD model fits assuming E(B-V)=0.07. The $\chi^2$ we obtained increased slightly over the E(B-V)=0.04 best fit models.

Last, we explored whether the fitting could be improved if we combined a white dwarf model with an accretion disk model. We found that some of the white dwarf plus disk combinations yielded distances close to 166 pc with a lower $\chi^2$. We have summarized some of these combination fits in Table 1. For E(B-V)=0.04, the best WD+disk fit leading to a distance in agreement with observed parallax is for a WD with $T = 46,000$ K, a disk with a mass accretion rate $\dot{M} = 1 \times 10^{-10} M_{\odot}$/yr, $i = 50°$, where the WD contributes 88% of the flux and the disk contributes the remaining 12%. This model fit is presented in Figure 1. We then carried out the same fitting but this time assuming E(B-V)=0.07 and found similar results for the disk but with a higher WD temperature: $T_{eff} = 55,000$ K.

Therefore, we conclude that the dominant source of the far UV radiation between 912 Å and 1660 Å is an accretion-heated white dwarf photosphere with $T_{eff} \approx 45 - 55,000$ K, $\log(g) = 8.3$ (depending on the reddening value).

## 5. Conclusions

We have presented evidence from our model fitting analysis of the combined *FUSE* + HST/GHRS spectrum of SS Cyg during quiescence that the source of the far ultraviolet continuum and absorption line radiation is the white dwarf's photosphere. The disk models that best fit the spectral data yield unreasonably large distances, at odds with the HST FGS parallax and indicate accretion rates far too high to be associated with dwarf nova quiescence. The photosphere models give effective temperatures of 45,000 to 55,000 K for a reddening of 0.04 and 0.07 with the inclusion of a low mass accretion rate disk in agreement with the quiescent state. Unfortunately, the lack of a clear detection of absorption lines due to accreted metals and helium in the WD atmosphere prevents a determination of both the rotational velocity of the white dwarf and the abundance of metals in its accreted atmosphere.

Our derived temperature for the white dwarf in SS Cygni is well above the presently

estimated average temperature (∼30,000 K) for white dwarfs in dwarf novae above the CV period gap. Compared with the temperatures of white dwarfs in dwarf novae whose orbital periods are close to the period of SS Cygni, the white dwarf in TT Crt is cooler (40,000 K; (Sion et al. 2008)) while the white dwarf in Z Cam is hotter (57,000 K; (Hartley et al. 2005)). If the accretion rate scales with the orbital period, then the temperatures should be comparable. It is interesting that the white dwarfs in dwarf novae with $P_{orb} < 360$ mins are cooler than 40,000 K while the hottest white dwarfs in dwarf novae are found at $P_{orb} > 360$ mins.

At $P_{orb} = 6.6$ h, the $T_{eff}$ of the WD in SS Cygni lies within the range expected from compressional heating for an average $\dot{M}$, $< \dot{M} >$, obtained from typical interrupted magnetic braking laws for white dwarf masses between $0.6M_{\odot}$ and $1.0M_{\odot}$ (Townsley & Gänsicke 2009). A linear extrapolation to $P_{orb}$, of the predicted $T_{eff}$ for $P_{orb} = 6.6$ h, corresponds to an average mass transfer rate of $< \dot{M} > \sim 10^{-8} M_{\odot}$/yr which is at the high end of the range of mass transfer rates associated with the nova-like variables, as determined from their optical disk luminosities (Warner 1995). Interestingly, the braking laws of Andronov et al. (2003) and Ivanova & Taam (2004) either fall drastically short or exhibit a downturn, respectively, of yielding the $< \dot{M} >$ implied by the WD $T_{eff}$, while the Howell et al. (2001) law steeply increases at constant $P_{orb} \sim 5$ h. One cannot rule that other significant sources of heating of the white dwarf besides compression are operating such as possible nuclear burning. It seems clear that more white dwarf temperatures are needed in dwarf novae and nova-like variables at long $P_{orb}$ before definitive conclusions can be drawn.

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Table 1. Synthetic Spectral Model Fits

| $Log(\dot{M})$ $< M_{\odot}/yr >$ | $i$ $< deg >$ | $T_{eff}$(WD) $< K >$ | $\chi^2$ | $d_{model}$ $< pc >$ | WD(%) | disk(%) | E(B-V) |
|---|---|---|---|---|---|---|---|
| -8.0 | 41 | — | 1.331 | 862 | — | 100 | 0.04 |
| -8.0 | 60 | — | 1.227 | 629 | — | 100 | 0.04 |
| -9.0 | 41 | — | 1.989 | 308 | — | 100 | 0.04 |
| -9.0 | 60 | — | 2.690 | 216 | — | 100 | 0.04 |
| -9.5 | 41 | — | 6.477 | 157 | — | 100 | 0.04 |
| -9.5 | 50 | — | 8.036 | 142 | — | 100 | 0.04 |
| -9.5 | 60 | — | 9.122 | 106 | — | 100 | 0.04 |
| -8.0 | 41 | — | 1.615 | 741 | — | 100 | 0.07 |
| -8.0 | 60 | — | 1.810 | 541 | — | 100 | 0.07 |
| -9.0 | 41 | — | 3.562 | 265 | — | 100 | 0.07 |
| -9.0 | 60 | — | 4.754 | 186 | — | 100 | 0.07 |
| — | — | 40,000 | 1.637 | 138 | 100 | — | 0.04 |
| — | — | 47,000 | 1.990 | 167 | 100 | — | 0.04 |
| — | — | 46,000 | 1.451 | 139 | 100 | — | 0.07 |
| — | — | 55,000 | 1.600 | 164 | 100 | — | 0.07 |
| -10.5 | 50 | 41,000 | 1.490 | 143 | 97.6 | 2.4 | 0.04 |
| -10 | 50 | 46,000 | 1.258 | 173 | 88.0 | 12.0 | 0.04 |
| -9.5 | 50 | 55,000 | 1.255 | 233 | 66.3 | 33.7 | 0.04 |
| -10.5 | 50 | 49,000 | 1.429 | 149 | 98.4 | 1.6 | 0.07 |
| -10 | 50 | 55,000 | 1.385 | 172 | 91.0 | 9.0 | 0.07 |
| -9.5 | 50 | 70,000 | 1.630 | 222 | 72.4 | 27.6 | 0.07 |

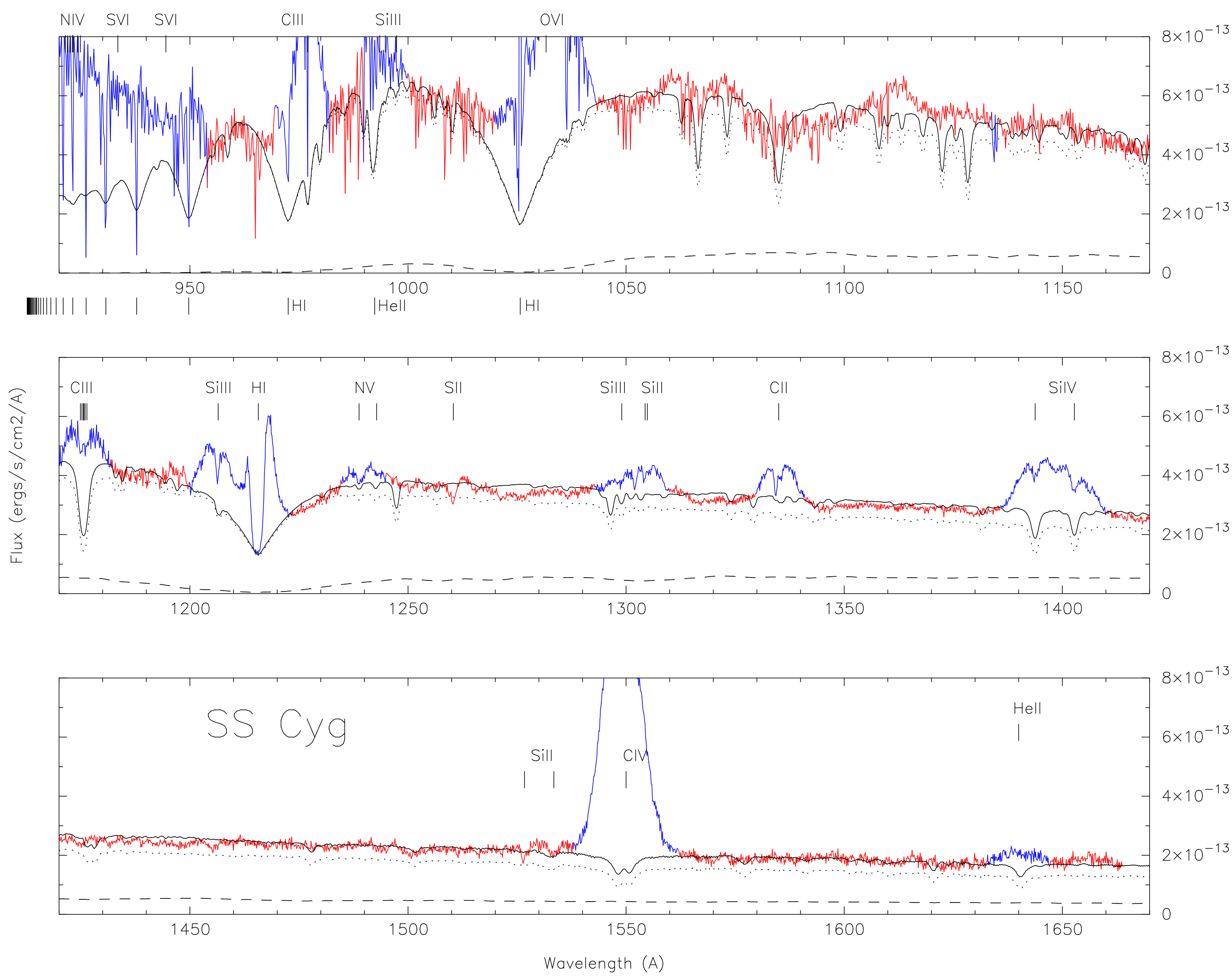


Fig. 4.— The combined spectrum of SS Cyg (in red) dereddened assuming E(B-V)=0.04 is shown with a composite WD+disk synthetic spectrum (in solid black). The WD model (dotted line) has $M_{wd} = 0.8 M_\odot$ (corresponding to $Log(g) = 8.3$), $T_{eff} = 46,000$ K, solar composition and a projected rotational velocity of 200km/s. The dashed line is the contribution from the accretion disk model. The disk model has a mass accretion rate $\dot{M} = 10^{-10} M_\odot$/yr and an inclination $i = 50°$. The $\chi^2$ obtained is 1.258 and the resulting distance is 173 pc. The WD contributes 88% of the FUV flux, while the disk contributes the remaining 12%. The excess of flux around 1060-1080 Å , and 1110-1130 Å might be due to some emission from S IV (1063, ∼1073 Å), Si IV (1066Å), Si III (∼1108-1113 Å), and Si IV (1122.5, 1128.3